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Porous Media Based Model for Deep Frying Potato Chips in a Vacuum

Diana Mitrea

Cornell University
Master's of Engineering, Biological Engineering
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Advisor, Ashim Datta

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Abstract

Deep-fat fried foods, such as potato chips, are prevalent in modern consumption habits. Low-pressure deep-fat frying has become increasingly popular in today's food products industry, and is used extensively by some of the largest potato chip manufacturers. Notably, an alternative technology has emerged: frying in a vacuum. The alternative approach allows frying to occur at much lower temperatures than regular atmospheric temperatures. Further, as shown in this paper, the alternative process -- in application to the potato chip industry-- reduces the amount of the carcinogen acrylamide formed process as compared to current practices, a noteworthy advantage.

To conduct the comparative analysis, a theoretical model was formulated and implemented using commercial software in order to further refine our understanding of the principles supporting low-pressure (vacuum) frying. The model can assist our understanding by presenting analyses that can be instrumental in determining the optimal operating parameters, such as oil temperature and pressure. As a starting point, an existing model of atmospheric potato chip frying was utilized and subsequently modified and improved upon to reflect more appropriate and accurate behavior under vacuum frying. The modeling results for moisture content, acrylamide content, and additional measures are then compared to existing measures from previous experiments for potato chip frying in a vacuum. The analysis shows that acrylamide formation is significantly reduced by vacuum frying at the lower temperature. The analysis performed also indicates that the moisture content profiles for the new process cook more quickly under the vacuum process as compared to the atmospheric process.

In addition, the idea of frying potato chips in vacuum as a potential food source for astronauts is explored. Astronauts have indicated they become tired of packaged foods on long space flights, but still require a constant stream of nutrition and energy sources; thus, the use of vacuum frying technology may be of interest to international space programs. As such, an analysis of this application is discussed, and the results of frying in space are compared to atmospheric and vacuum frying as well.

Introduction

Potato chips have become an increasingly popular snack food in the United States; unfortunately they are not entirely healthy snack. Potato chips, as processed by most major food processing companies, contain unhealthy levels of oil content and even have trace amounts of a known carcinogen, acrylamide. As an alternative, the vacuum frying method of cooking potatoes or other vegetables has become more prevalent, because the process claims to result in less oil content and yield less acrylamide formation. The only difference between regular (atmospheric) deep-fat frying of foods and low pressure (vacuum) deep-fat frying is the sealed container that is depressurized. This allows water to boil and evaporate at a much lower temperature than the atmospheric 100˚C. In fact, at the lower temperatures needed to cook the potatoes there is lower acrylamide formation, a noteworthy health advantage for modern consumers of these food stuffs.

In order to conduct a comparative analysis of the two frying methods, an accurate mathematical model of vacuum frying potato chips needed to be formulated and implemented to support the aforementioned claims of decreased health risks attributable to the new process. Further, such a model may be instrumental in complementing our existing understanding of deep-fat frying. The model demonstrates qualities and properties of the vacuum frying process that cannot be observed in *physical* experiments. However, the modeling of deep-fat frying under vacuum is complicated by the additional complexity induced by operating at significantly low pressure levels. The low ambient pressure causes the rate of evaporation to be much larger compared to atmospheric frying, ultimately leading to non-convergence of the model. Moreover, complexities also arise from the fact the majority of the oil absorbed in the process actually occurs <u>*after*</u> the frying has been complete (Bouchon and Pyle, 2005).

Another reason to look at vacuum frying besides the health benefits is the possibility that astronauts could use deep-fat frying to cook their food when traveling through space or for missions to the moon/Mars. There are many problems that astronauts face while on missions including low nutrition and losing weight. Deep fried foods would pose as a more appealing option to consume rather than the packaged foods. This is done in partner with Professor Jean Hunter in the Biological Engineering department at Cornell University.

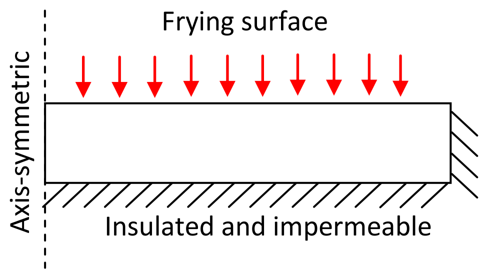
The atmospheric model (Halder, A., 2002) model for deep-fat potato chip frying demonstrates moisture content, temperature profiles and oil content as well as acrylamide formation. However, when attempting to incorporate the oil absorption portion into the vacuum frying model, the high evaporation rate of water posed difficulties. Taking this into account, in this particular model, oil absorption has been ignored. Also, their model assumes a potato mix rather than raw potato which has been changed for this model.

Objectives and Overview

The following are the objectives of the project:

(1) Modify the atmospheric deep-fat frying model of potato mix (Amit Halder, 2007) to demonstrate vacuum deep-fat frying of raw potato;
(2) Compare the results with existing experiments done in a vacuum (moisture, acrylamide, etc);
(3) Demonstrate the behavior of a potato deep fried under conditions in a space shuttle or on the moon.

Figure 1: Schematic of the model showing boundary conditions. The potato is assumed to be symmetric along the axis in a disk-shape. The thickness of the potato chip is assumed to be 1.5 mm and 4.5 cm in diameter.



Assumptions:

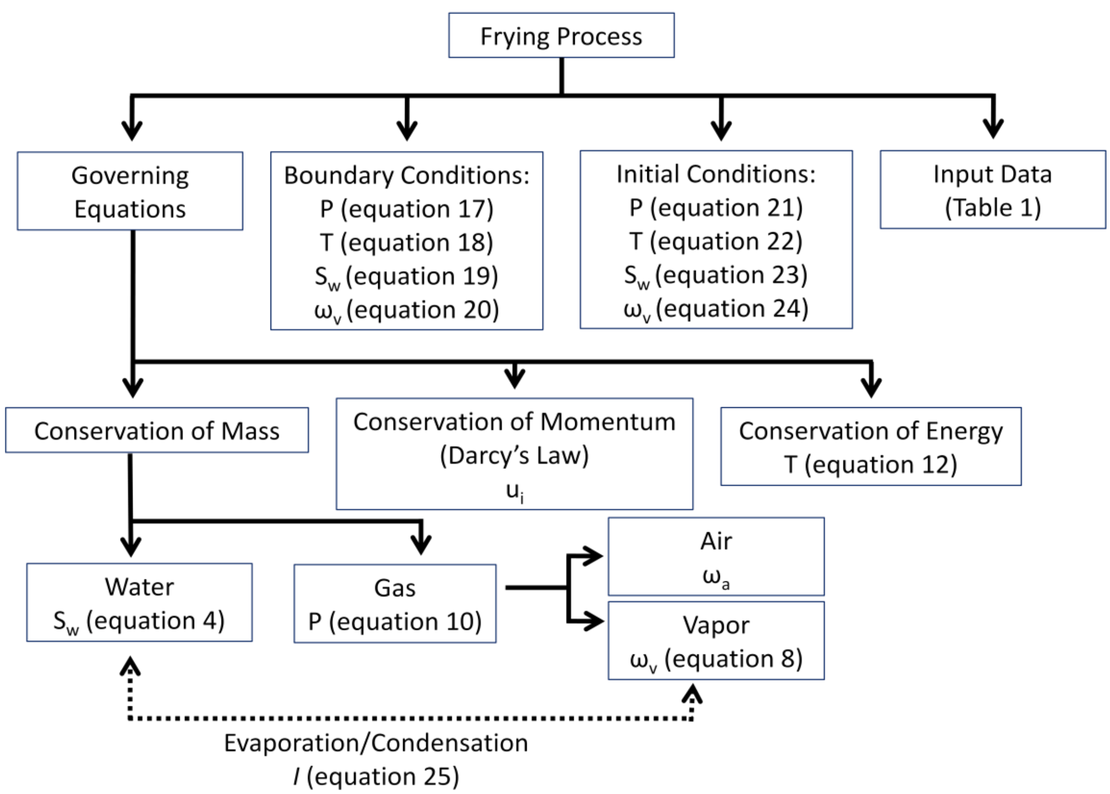
- Constant pressure at the surface
- Convective transfer of vapor
- Thermal equilibrium between all phases
- Shrinking or structure changes are not considered

Transport:

- Water: pressure and capillary driven
- Vapor: Pressure driven and binary diffusion in air
- Energy: conduction, flow and latent heat

Phase change: non-equilibrium

Figure 2: Putting together the model [modified from (Amit Halder, 2007)]



Governing Equations

All governing equations are used from the original atmospheric frying model (Amit Halder, 2007) and unless specified, no changes have been made. There are three main groups of governing equations: mass balance equations, momentum balance equations and energy balance equations. To visualize the three coming together in the model, see Figure 2.

Mass Balance Equations

Mass balance equations focus on the concept that each molecule must originate from somewhere and must go somewhere. There is neither spontaneous creation nor spontaneous destruction of any element in the model. There are three masses considered: water, gas and solid (in this model, oil is not taken into account). The solid is porous, with water and gas occupying the space in the pores. When heated, the solid remains the same, but the water evaporates into water vapor to become part of the gas phase.

We begin by defining ΔV_i as the volume occupied by water or gas. *i* can be substituted as either water (w) or gas (g). Porosity (ϕ) can be defined as the fraction of the pores over the total volume. In other words, the space not occupied by the solid divided by the total volume,

$$\varphi = \frac{\sum_{i=w,g} \Delta V_i}{\Delta V} \tag{1}$$

Following equation (1), we can define saturation of water or gas (S_i) by equation (2). This is a simple percentage fraction of the amount of volume occupied by either water or gas divided by the space not occupied by the solid.

$$S_i = \frac{\Delta V_i}{\varphi \Delta V} \tag{2}$$

It follows that the sum of these two fractions must be equal to one.

$$S_w + S_g = 1. \tag{3}$$

Using the following mass balance equation, the saturation of water can be found. The saturation of gas, S_g is then calculated from equation (3).

$$\frac{\partial}{\partial t}(\varphi \rho_w S_w) + \nabla \cdot (u_w \rho_w) = \nabla \cdot \left[D_{w,cap} \nabla(\varphi \rho_w S_w)\right] - \dot{I} \tag{4}$$

In the above equation, $\dot{I}$ is the evaporation rate and will be addressed in equation (25).

The difference between gas pressure (outside the potato) and capillary pressure (inside the potato) is what causes the flux of liquid water. Darcy's law is used to calculate the total flux of the liquid water through the porous medium as follows,

$$n_w = -\rho_w \frac{k^p_{in,w} k^p_{r,w}}{\mu_w} \nabla(P - p_{cap})$$

$$= -\rho_w \frac{k^p_{in,w} k^p_{r,w}}{\mu_w} \nabla P + \rho_w \frac{k^p_{in,w} k^p_{r,w}}{\mu_w} \frac{\partial p_{cap}}{\partial S_w} \nabla S_w \quad (5)$$

The first term in the equation is the velocity of the water (u_w) which was seen in equation (4). This term will also be revisited in the moment balance equation section. The second term is simplified by writing it in terms of capillary diffusivity, $D_{w,cap}$, which is seen here,

$$D_{w,cap} = \frac{k^p_{in,w} k^p_{r,w}}{\mu_w} \frac{\partial p_{cap}}{\partial S_w} \quad (6)$$

Therefore, equation (5) can be simplified to: $n_w = -\rho_w u_w + \rho_w D_{w,cap} \nabla S_w$. (7)

As the potato is heated, water boils, then evaporates, and eventually becomes water vapor. The gas inside the potato is a mixture of water vapor and air. Mass fractions ω_v and ω_a represent the two different gasses. Concentrations of the water-vapor and air change during frying time and the following mass conservation equation (8) can be used with binary diffusion,

$$\frac{\partial(\varphi \rho_g S_g \omega_v)}{\partial t} + \nabla \cdot (u_g \rho_g \omega_v) = \nabla \cdot \left(\varphi S_g \frac{C_g^2}{\rho_g} M_a M_v D_{eff,g} \nabla x_v\right) + \dot{I} \quad (8)$$

Consequently, much like equation (3) referring to the saturation of water and gas, the sum of the two mass fractions ω_v and ω_a must be equal to one.

$$\omega_v + \omega_a = 1 \quad (9)$$

For the gas phase, the total pressure inside the potato is calculated using a mass balance equation. Total pressure is summed to include all of the gasses (water vapor and air). The changes in pressure can be directly related to the evaporation rate, $\dot{I}$.

$$\frac{\partial}{\partial t}(\varphi S_g \rho_g) + \nabla \cdot \left(-\rho_g \frac{k^p_{in,g} k^p_{r,g}}{\mu_g} \nabla P\right) = \dot{I} \quad (10)$$

Using the above equations, S_w, S_g, fractions ω_v and ω_a are all calculated by the program. A few other unknowns must be addressed to fully solve the model.

Momentum Balance Equation

Momentum balance considers the movement of water and water vapor through the potato while having air come in to fill the space remaining. The velocity of the water and gas as they move through the porous potato are described by Darcy's Law. The movement is, as mentioned before, due to the pressure gradient.

$$u_i = -\frac{k_{in,i}^{p} k_{r,i}^{p}}{\mu_i} \nabla P \quad (11)$$

Again, *i* can be either water or gas. Our model considers that water vapor and air have the same velocity and move as one when in the gas phase.

Energy Balance Equations

Temperature is another important variable. The heat of the oil travels through the potato and some is transferred to heat the solid, while other heats the water to convert it into water vapor. All phases must have the same temperature. The water, solid and gas must all be at a temperature equilibrium. Therefore, the following energy balance equation arises,

$$\frac{\partial}{\partial t}\left(\rho_{eff}\, c_{p,eff}\, T\right) + \nabla \cdot \left(\left(\rho c_p u\right)_{fluid} T\right) = \nabla \cdot \left(k_{eff} \nabla T\right) - \lambda \dot{I} \quad (12)$$

Where λ is latent heat of evaporation. This is a very important variable when discussing vacuum frying since this value changes with each pressure. The different values used in this paper can be found in Table 2 (to follow).

The effective properties (density, specific heat capacity and thermal conductivity) of the mixture of liquid, solid and gas are constantly changing through the frying process. This is because the mass fractions are constantly changing (liquids changing into gas, etc). Thus, the properties of the mix is calculated by averaging the phase properties using their mass fractions accordingly (subscript 's' refers to the solid potato properties):

$$\rho_{eff} = (1-\varphi)\rho_s + \varphi(S_w \rho_w + S_g \rho_g) \quad (13)$$
$$c_{p,eff} = m_g\left(\omega_v c_{p,v} + \omega_a c_{p,a}\right) + m_w c_{p,w} + m_s c_{p,s} \quad (14)$$
$$(\rho c_p u)_{fluid} = \left[\rho_w u_w - D_{w,cap} \nabla(\varphi S_w \rho_w)\right] c_{p,w} + \rho_g u_g (\omega_v c_{p,v} + \omega_a c_{p,a}) \quad (15)$$
$$k_{eff} = (1-\varphi)k_s + \varphi[S_w k_w + S_g(\omega_v k_v + \omega_a k_a)] \quad (16)$$

Boundary and Initial Conditions

Boundary conditions are essential in the model since their implementation causes the change in the potato chip. The slab is considered axis-symmetric on the left side to simulate a 4.5 cm in diameter slab of 1.5 mm thickness. The top of the potato chip is heated as shown in Figure 1. The top of the potato is also open to the ambient pressure that the frying is completed in. The boundary conditions for the frying model are as follows,

Boundary condition for equation (10):

$$P_{surf} = P_{amb} \quad (17)$$

Boundary condition for equation (12):

$$q_{surf} = h\left(T_{amb} - T_{surf}\right) - \left(\lambda + c_{p,w} T\right) n_{w,surf} - c_{p,v} T n_{v,surf} \quad (18)$$

Boundary condition for equation (4):

$$n_{w,surf} = h_m \varphi S_w (\rho_{g,surf}\, \omega_{v,surf} - \rho_{v,amb}) \quad (19)$$

Boundary condition for equation (8):

$$n_{v,surf} = h_m \varphi S_g (\rho_{g,surf}\, \omega_{v,surf} - \rho_{v,amb}) \quad (20)$$

The pressure in equation (17) is exactly what is being changed depending on atmospheric or vacuum frying. A list of pressures can be found in Table 2. In frying the heat transfer occurs at the surface of the potato and the surrounding oil given by equation (18). Equations (19) and (20) explain how water and water vapor leave the surface of the potato.

Initial conditions are given below for the same equations. These are all considered at time t = 0 seconds.

Initial condition for equation (10): $P = P_{amb}$ (21)
Initial condition for equation (12): $T = T_{amb}$ (22)
Initial condition for equation (4): $S_w = 0.991$ (23)

Initial condition for equation (8): ω_v (vapor mass fraction) changes depending on the frying pressure. Using $x_v = \frac{p_v}{p}$, the mole fraction of vapor, the vapor mass fraction can be calculated with M_v (mass of vapor/mol = 0.018 kg/mol) and M_a (mass of air/mol = 0.029 kg/mol) as follows:

$$\omega_v = \frac{x_v M_v}{x_v M_v + (1 - x_v) M_a} \quad (24)$$

Phase Change of Water

As water changes from liquid to vapor, there is a certain rate at which it evaporates and leaves the potato. A non-equilibrium expression for evaporation of water is given by:

$$\dot{I} = K(\rho_{v,eq} - \rho_v) \quad (25)$$

Where K is the rate constant of evaporation. The equation (25) expresses the evaporation rate explicitly and is easier to implement in commercial software models.

Acrylamide Formation

The entire kinetics acrylamide formation is not fully understood. However, it is known that acrylamide forms when food is cooked at high temperatures. Frying, being done at extremely high temperatures is an ideal candidate for studying acrylamide formation. Certain pre-treatments of the potatoes, such as pre-soak, have been shown to reduce the amount of acrylamide (Rosana Moreira, 2002). Also, it has been shown experimentally that less acrylamide forms in vacuum frying than in atmospheric frying (Claudia Granda, 2005). Being a carcinogen, the reduction of acrylamide in foods is extremely important.

For our model, potato chip acrylamide formation is demonstrated using Claudia Granda's equations. Two separate equations were used; one for vacuum pressure frying and one for atmospheric pressure frying. The atmospheric pressure (101kPa) acrylamide formation:

$$k(T) = 14.9 \exp\left(\frac{-2625.8}{T}\right) \tag{26}$$

$$C(t) = A_0 + \frac{A}{1+exp\left[-k(T)(t-t_o)\right]} \tag{27}$$

k(T) is the reaction rate equation, describing the rate at which acrylamide is formed in the potato. C(t) is the amount of acrylamide (in ppb) at time t. The variable A is the equilibrium acrylamide content (maximum acrylamide that can form) and t_0 is the time constant where $C(t_0)$= 0.5A. Lastly, A_0 is the amount of acrylamide before frying begins (in our case, this is zero). Table 1 shows the values of the constants in the above equation. The constants were given by Granda and Moreira and these are the only ones available for the model. Unfortunately, this limits the temperatures at which the acrylamide reaction model can be run.

Table 1: Acrylamide model constants (Claudia Granda, 2005)

Temperature (C)	A (ppb)	t_0 (s)
150	484	257
165	847	178
180	1123	114

As can be seen from equation (27), the amount of acrylamide levels off after a certain amount of time and will not increase further. This is equal to the constant value 'A'. However, this was not the case for vacuum frying. Granda and Moreira observed a different behavior for acrylamide formation in vacuum pressure frying. The acrylamide formed in vacuum frying did not seem to have a plateau after a certain amount of time. Therefore, a different set of equations has been implemented. Vacuum pressure (1kPa) acrylamide formation:

$$k(T) = 505498 \exp\left(-\frac{7344.14}{T}\right) \tag{28}$$

$$C(t) = C_o \exp(\mathrm{k(T)}) \tag{29}$$

The amount of acrylamide in vacuum frying did not demonstrate a leveling out. This could also be due to the fact that it would take a longer amount of time to find the equilibrium and the experiments were not run long enough to display this.

These equations and their parameters and constants were derived by simply finding the best-fit line to the experimental data curve. The issue here is that the experiments are not exact and the best-fit curve might not be the most precise way to demonstrate acrylamide formation. More knowledge on the kinetics of acrylamide formation are needed; what are the reactants? how much energy is required to create this product? is there a limiting factor?

Input Parameters

The many constants needed for the different properties of water, vapor, air and potato solid can be found listed in Table 2. The physical and thermal properties used are from a raw potato as opposed to the potato mix used in the atmospheric frying model (Halder, A., 2002); the reason being that no experimental data existed in a vacuum for potato mix. Diffusivity, specific heat, thermal conductivity and relative permeability are functions dependent on other properties at the time of the frying. These are listed below in equations (30) – (35).

Diffusivity of water through the porous media of the potato is written as a function of the moisture content (Amit Halder, 2007). The equation is as follows,

$$D_{w,cap} = 1 \times 10^{-8} \exp(-2.8 + 2.0M) \tag{30}$$

Specific heat capacity of liquid water and water-vapor can be defined as functions of temperature (Amit Halder, 2007). This dictates how much heat energy the water or water-vapor can hold.

$$c_{p,w} = 4176.2 - 0.0909(T - 273) + 5.4731 \times 10^{-3}(T - 273)^2 \tag{31}$$

$$c_{p,v} = [32.22 + 0.192 \times 10^{-2}(T - 273) + 1.054 \times 10^{-5}(T - 273)^2 - 3.594 \times 10^{-9}(T - 273)^3]\frac{10^3}{M_v} \tag{32}$$

Thermal conductivity of liquid water is also given as a function of temperature (Amit Halder, 2007).

$$k_w = 0.57109 + 1.762 \times 10^{-3}(T - 273) - 6.7036 \times 10^{-3}(T - 273)^2 \tag{33}$$

Relative permeability depending on the amount of liquid water in the system is given by Bear (1972):

$$k_{r,g}^{p} = \begin{cases} 1 - 1.1S_w & S_w < 1/1.1 \\ 0 & S_w > 1/1.1 \end{cases} \tag{34}$$

$$k_{r,w}^{p} = \begin{cases} \left(\frac{S_w - S_r}{1 - S_r}\right)^3 & S_w > S_r \\ 0 & S_w < S_r \end{cases} \tag{35}$$

Table 2: Input parameters for the deep-fat frying model [modified from (Amit Halder, 2007)]

Parameter	Symbol	Value	Units	Source
Density				
Water	ρ_w	998	kg m^{-3}	
Vapor	ρ_v	Ideal gas	kg m^{-3}	
Air	ρ_a	Ideal gas	kg m^{-3}	
Solid	ρ_s	1528	kg m^{-3}	Farkas et al. 1996b
Specific heat capacity				
Water	c_{pw}	Equation(31)	J kg^{-1} K^{-1}	Lewis (1987)
Vapor	c_{pv}	Equation (32)	J kg^{-1} K^{-1}	Lewis (1987)
Air	c_{pa}	1006	J kg^{-1} K^{-1}	Choi and Okos (1986)

Solid	c_{ps}	1650	J kg^{-1} K^{-1}	Choi and Okos (1986)
Thermal conductivity				
Water	k_w	Equation (33)	W m^{-1} K^{-1}	Choi and Okos (1986)
Vapor	k_v	0.026	W m^{-1} K^{-1}	Choi and Okos (1986)
Air	k_a	0.026	W m^{-1} K^{-1}	Choi and Okos (1986)
Solid	k_s	0.21	W m^{-1} K^{-1}	Choi and Okos (1986)
Intrinsic permeability				
Water	$k^p_{in,w}$	10^{-16}	m^2	Ni and Datta (1999)
Air and vapor	$k^p_{in,g}$	2×10^{-16}	m^2	Ni and Datta (1999)
Relative permeability				
Water	$k^p_{r,w}$	Equation (34)		Bear (1972)
Air and vapor	$k^p_{r,g}$	Equation (35)		Bear (1972)
Capillary diffusivity				
Water	$D_{w,cap}$	Equation (30)		Ni and Datta (1999)
Viscosity				
Water	μ_w	0.988×10^{-3}	Pa s	
Air and vapor	μ_g	1.8×10^{-5}	Pa s	
Heat transfer coefficient	h	100	W m^{-2} K^{-1}	
Mass transfer coefficient	h_m	0.01	m s^{-1}	
Latent heat of vaporization				
9888 Pa	λ	2.394×10^6	J kg^{-1}	
16661 Pa	λ	2.403×10^6	J kg^{-1}	
70 kPa	λ	2.283×10^6	J kg^{-1}	
101 kPa	λ	2.26×10^6	J kg^{-1}	
Porosity	ϕ	0.880		
Vapor diffusivity in air	$D_{eff,g}$	2.6×10^{-6}	m^2 s^{-1}	
Oil temperature	T_{oil}	Varies	K	
Ambient pressure	P_{amb}	Varies	Pa	

Model Validation

For all computer generated models, model validation is extremely important. This is done by comparing the model results to experimental results. Unfortunately, to date, there have been few vacuum frying experiments completed. Moreover, even fewer have been conducted on raw potato specifically. As such, the experimental data used for verification in this report is taken from two research papers written by Rosana Moreira that cover the fairly narrow space of vacuum frying of potato chips.

The first paper compared changes in moisture of the potato at different frying times and at different temperatures. For model output concerning moisture content, the model results were verified against Moreira's experimental findings detailed in her research paper. Specifically, the model results were verified by comparing the moisture at time t as a percentage of the initial moisture. A graphical comparison of the model results overlaid on top of the experimental results found by Garayo and Moreira is depicted in Figure 3 at the end of this document. Depicted are the model and experimental results for two pressures, 16kPa and 9kPa, as well as, two temperatures, 132°C and 118°C. For the purpose of avoiding too many points on one graph, other experimental results have been excluded. Nevertheless, the implemented model's general trend is similar to the experimental figures, as depicted in Figure 3.

A close look at the shape of the graph of both the experimental results and the model results indeed show that the model is indeed very close to the actual data. The time at which moisture is completely gone (the t for which M(t)=0) is almost exactly the same in the experiment and in the model. The data sets for 118°C are the best match.

There is a lot of variability in this data set especially since the experimental data from the graph has only been taken from one paper (Rosana Moreira 2002). This is only one experiment done by one person. Thus, to further validate the accuracy of the model, more experiments are needed for different pressures and different temperatures.

Model Results

The full model results begin in Figure 4 and continue through the rest of the paper. These figures are generated as output from the model and several comparisons are done between results for varying pressures and temperatures. The three variables to be compared are: the moisture content over time, the temperature profiles of the potato through the frying process, and finally, the acrylamide formed over time.

Figure 4 shows the percent moisture content over time during the frying process at varying pressures. As can be seen, the water leaves the chip more quickly in a vacuum than in atmospheric frying. This is due to the different latent heat of vaporization of water value. Thus, water boils at a lower temperature. The water begins to vaporize and leaves the chip before it reaches 100˚C. The chip cooks at a lower temperature and in turn, faster in a vacuum.

Figure 5 shows the average temperature of the chip during frying. The main difference between atmospheric and vacuum frying temperature profiles is the temperature at which water begins to evaporate. The atmospheric frying indicates a plateau at about 343K. 16kPa frying indicates a plateau at about 325K and 9kPa loses water at about 319K. The temperature of the chip does not increase because all energy is being used to change water into water vapor. Evaporation continues until about 20% of the moisture remains (Figure 4) and then some of the heat also begins to transfer to the solid potato as well. Additionally, atmospheric frying has a much longer evaporation time than the vacuum frying. The time at which the chip remains at a constant temperature is longer for atmospheric frying than for vacuum frying (Figure 5).

After the plateau has stopped, the temperature profiles in Figure 5 begin to slowly increase upwards. There is some water remaining in the chip, so not all of the heat energy is being used to increase the potato's temperature – some is still used to evaporate the remaining water. This is indicated in the gentle slope portion of the curve. Once there is no more water remaining (M(t) = 0, reference Figure 4), the slope of the temperature curve increases abruptly and will continue increasing until the final temperature is reached.

What is unique in the temperature profiles of the two vacuum pressures (9kPa and 16kPa) in Figure 5 is the first peak that occurs at approximately 20 seconds into frying. This is due to the small K (rate constant of evaporation – equation (25)). The K is not large enough for equilibrium to be reached. This causes heat to raise the temperature of the chip instead of transferring energy to evaporate the water into water vapor. This changes quickly enough and energy begins to heat the water as well. As soon as water begins to evaporate, the temperature drops slightly and plateaus as expected.

In Figures 6&7 the pressure is kept constant (16kPa) and the temperature is varied (118˚C, 132˚C, 144˚C). These figures depict the moisture content and the temperature gradient of the vacuum fried potato chip. Again, the results are as expected. The higher temperatures cause the moisture to be lost at a faster rate since there is more heat to be transferred from the higher oil temperature. With the pressure remaining the same, the temperature at which water evaporates is the same (first plateau in Figure 7). All the temperature curves are right on top of one another until most of the water is evaporated. On the other hand, the lower temperature (118˚C) does prevent this from happening at a faster rate. The first plateau of the temperature profile for 118˚C goes on for a longer period of time than for 144°C. Eventually, once all the water has evaporated, the temperature curves rise steeply and plateau at their corresponding peak temperatures. Obviously, none of them can go higher than the surrounding oil temperature.

Acrylamide Content

Figure 8 demonstrates differences in acrylamide formation. Acrylamide content is more difficult to implement because of the few constant values provided (Table 1). As it can be seen from equations (26)-(29), acrylamide formation depends on temperature. Small changes in temperature (such as between 125°C and 140°C) cause a significant increase in the amount of acrylamide. This is shown in the experimental data as well as the model results.

The acrylamide formation in a vacuum still varies from temperature to temperature. When compared to the experimental data from Granda and Moreira (see Figure 9), we note about 2x less acrylamide in our model than in their experiments. This is first and foremost due to the fact that the T in equations (26), (27), (28) and (29) are all considered constant and equivalent to the oil temperature at all times in their model. When implemented in our model, the T used is equal to the actual potato temperature, which changes over time as seen in Figures 5&7. The lower amount of acrylamide can also be due to the fact that the experiment is run at 1333 Pa. This pressure is lower than the vapor pressure (4173 Pa) which means that water is boiling even before the potatoes are put into the oil. This causes the chip to cook even before being placed into the oil. This could also cause the higher experimental values of acrylamide content.

The acrylamide content in atmospheric frying at three different temperatures (150˚C, 165˚C and 180˚C) is shown in Figure 10. These results are very close to the experimental results shown in Figure 11. Here, acrylamide forms until a certain level at which it levels off and becomes constant no matter how long the frying takes place. This is indicated as the constant value 'A' from equation (27).

Figure 12 shows the pressure effect on acrylamide formation. The amount of acrylamide formed during atmospheric frying increases rapidly and quickly surpasses that during vacuum frying conditions. Since the frying temperature is lower, the total amount of acrylamide formed (~200 ppb) is much lower than what has been shown before (Figure 10) for frying at much higher temperature. Acrylamide formation only depends on the temperature of the potato and thus, when fried at the same temperature, very little differences are expected to occur as shown in this figure.

From equation (27) and Table 1, it can be seen that an 'A' value is needed for atmospheric frying temperatures. A crude estimate of 207 ppb for the value of 'A' is used by applying the best-fit curve equation. Increasing or reducing this value will change the graph of the acrylamide formed during atmospheric frying. This of course, brings into question the validity of the differences between acrylamide formation at different pressures but at the same temperatures. Since acrylamide formation depends only on temperature gradients, there should be little differences between the graphs. Looking at Figure 5, the temperature does differ slightly depending on the pressure, but the end result is the same. However, the atmospheric frying is not done at such low temperatures and such a graph does not have much application in the food industry.

Figure 13 represents the acrylamide differences between vacuum frying and atmospheric frying when each is done at the appropriate temperature. As in all cases, atmospheric frying is done at a much higher temperature (165°C) than the vacuum frying (118°C). This graph is much more applicable to the food industry than the other figures since atmospheric frying cannot be done at 118°C.

The acrylamide differences here are easily observed. Acrylamide content in atmospheric frying is substantially larger that the acrylamide content of vacuum frying. The acrylamide content in Atmospheric frying reaches almost 10x that in vacuum frying. The health benefits can be best seen in Figure 13. As shown by this analysis, atmospheric frying contains more of the carcinogen than vacuum frying.

Potato Frying in Space (70kPa)

In addition to the taste and health benefits that vacuum frying poses, modeling vacuum frying allows us to consider what is happening while food is being cooked in space. Astronauts on long trips need to eat to maintain their health and energy. Packaged foods are extremely unappetizing and can lead the astronauts to eat less and avoid the un-appealing foods. Deep fried foods are delicious and also conveniently contain large quantities of fat and oils. This is a potential option for cooking in space. Space cooking would be done at an approximate 70kPa. At this lower pressure a temperature between 165°C (atmospheric) and 120°C (vacuum) was chosen: 150°C.

Figures 14, 15 and 16 depict the moisture content, temperature profile and acrylamide content graphs as demonstrated by the model. Since there is no experimental data done at this pressure, the full validity of these graphs cannot be determined. However, with experimental data above and below this pressure, there is a lot of certainty surrounding these values. At this lower pressure, the potato cooks faster even though the temperature at which this is done is lower than the atmospheric temperature. The form of the temperature profile follows closely that of previous temperature profiles.

In Figure 16, the acrylamide content corresponding to space frying, frying in vacuum and atmospheric frying is graphed. While there is still much more acrylamide forming in space frying than in vacuum frying, it is still significantly less than that in atmospheric frying.

Conclusion

The results of the multiphase porous model show the benefits of choosing low-pressure frying over atmospheric frying. The acrylamide content is reduced significantly in the low-temperature vacuum fried potato chip. Vacuum frying can definitely help us continue to eat deep fried foods, but without as much acrylamide.

Another benefit of vacuum frying is that cooking of the potato chip occurs at an even faster rate than atmospheric frying. The food industry is always looking at ways to improve their products without lowering their respective taste and health benefits. Vacuum frying has the potential to become a very valuable tool for the food industry in the future.

Having a valid multiphase porous model that demonstrates the results of deep-frying at different temperatures and pressures will help to optimize these parameters for the healthiest possible chip that is cooked in the most efficient way possible.

Future Work

To continue refining the model, oil content must be incorporated and further investigated. There have been many claims that vacuum frying reduces the oil content and a model showing this would be very beneficial. Unfortunately, the complex nature of oil absorption in the potato chip makes this a very difficult task. It has been shown that most of the oil absorption happens after frying has been completed, which adds additional parameters surrounding the cooling of the potato chip (Rosana Moreira, 2002). A possibility is to create another model centered on cooling the potato chip and importing the frying results to this program. A completely different mechanism will have to be implemented.

More experiments should be conducted to supplement the model and validate the results. The current experimental results available are limited. Varying the thickness of the potato chips would test the model further. Also, if possible, inserting a temperature probe into a potato before frying would allow a possible temperature profile to be used for comparison with the results of the model.

While the model has shown promising results, there is a lot of work that remains to be done on vacuum frying. The potential health benefits and taste benefits must continue to be explored experimentally to further advance the realism of the computer model.

Appendix: Figures

Figure 3: Comparing (Rosana Moreira 2002) values to model values. The experimental points were taken from the graphs in the paper and approximated to put into this diagram.

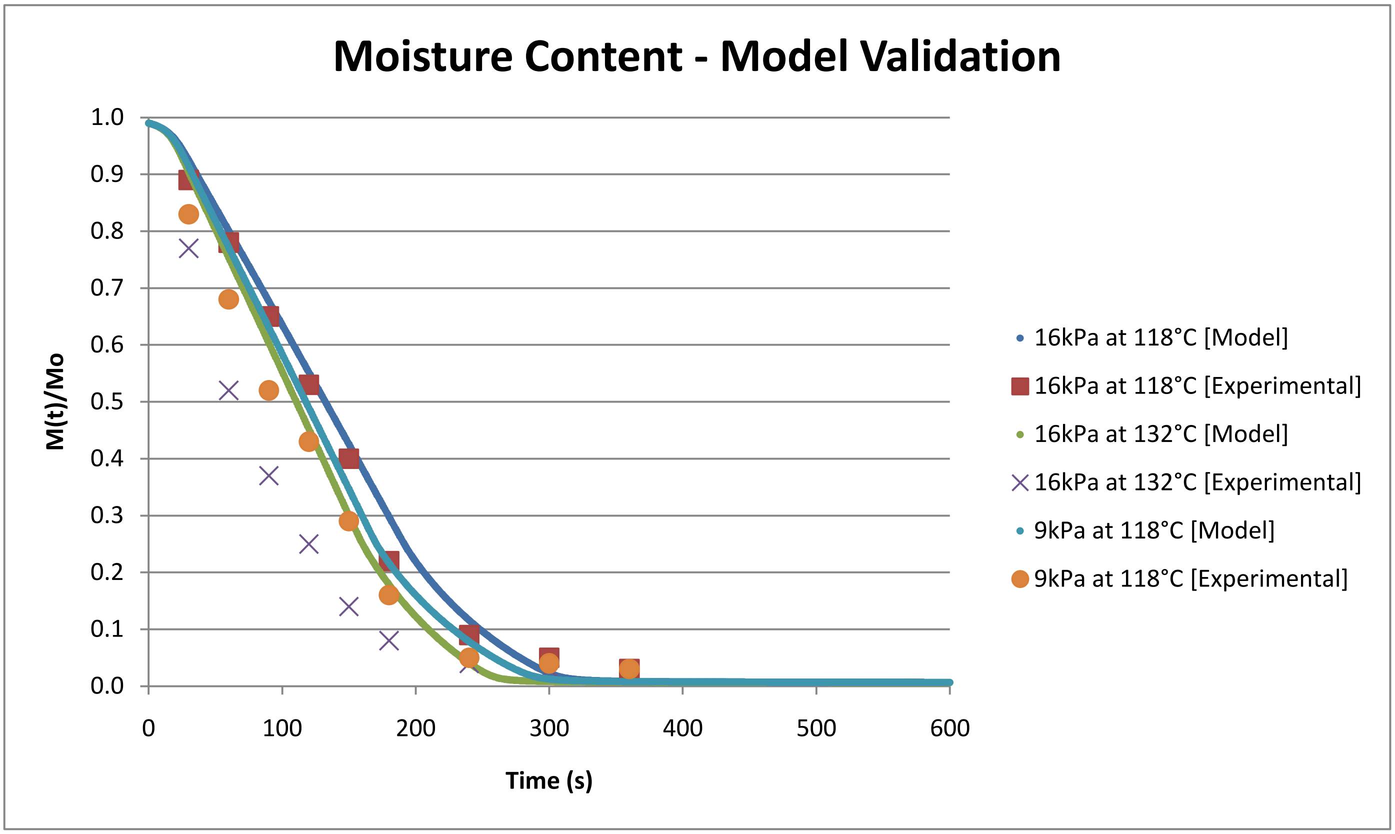
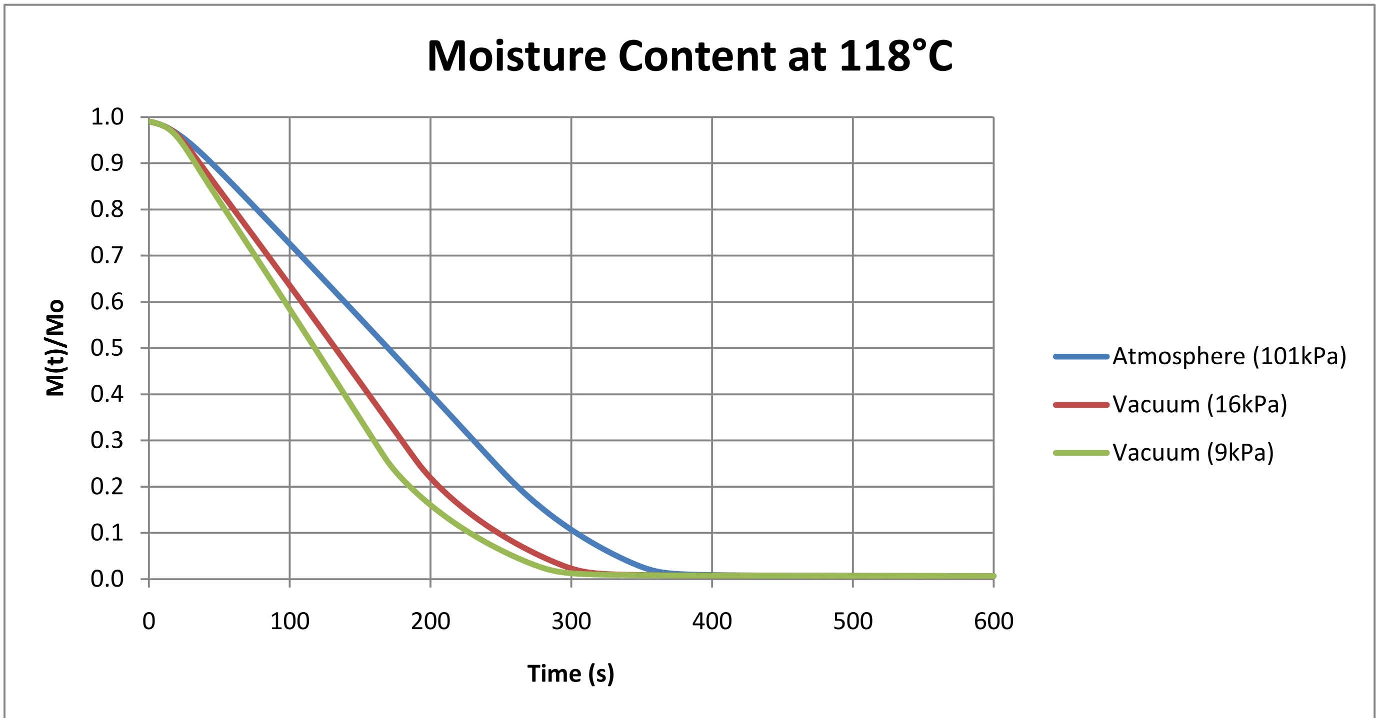


Figure 4: Moisture content as a percent of the original moisture of the potato over frying time.



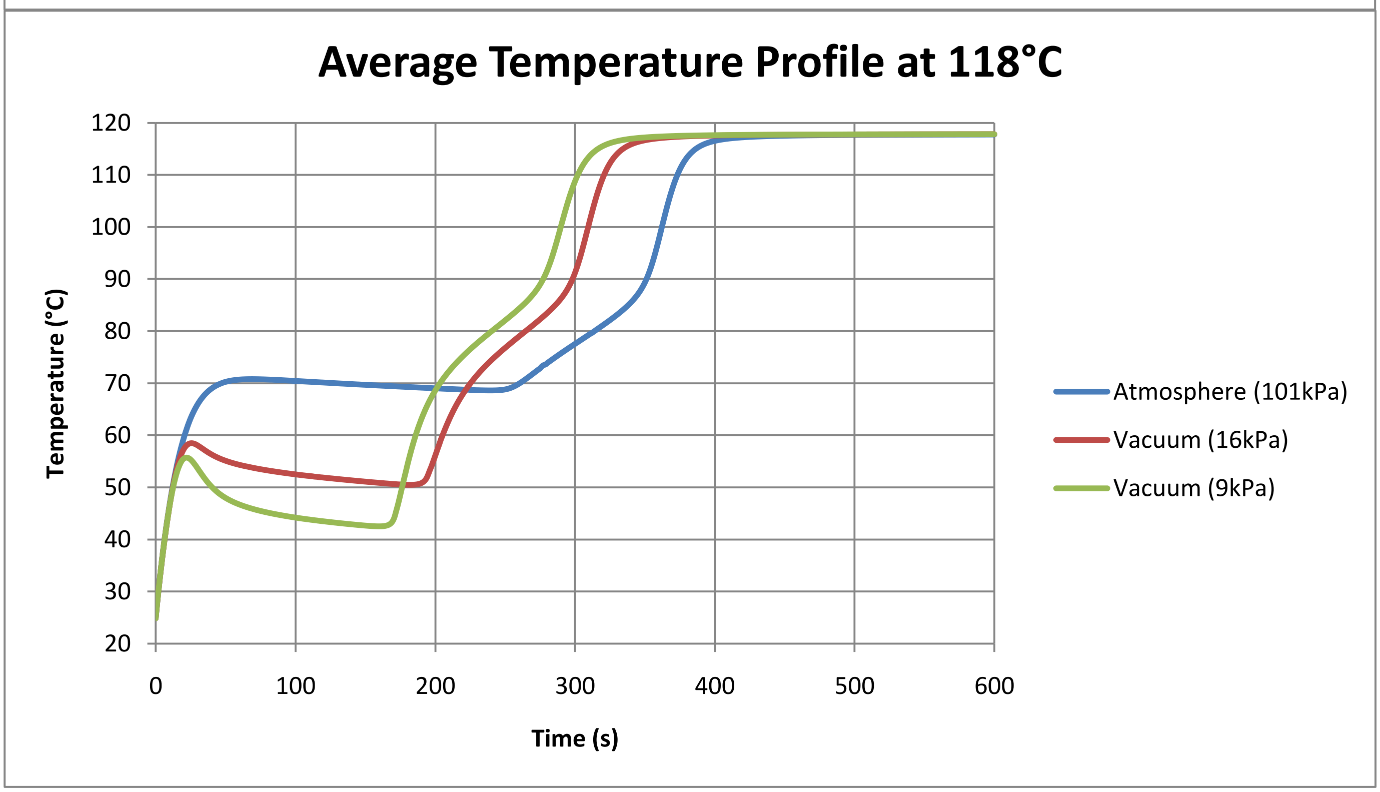
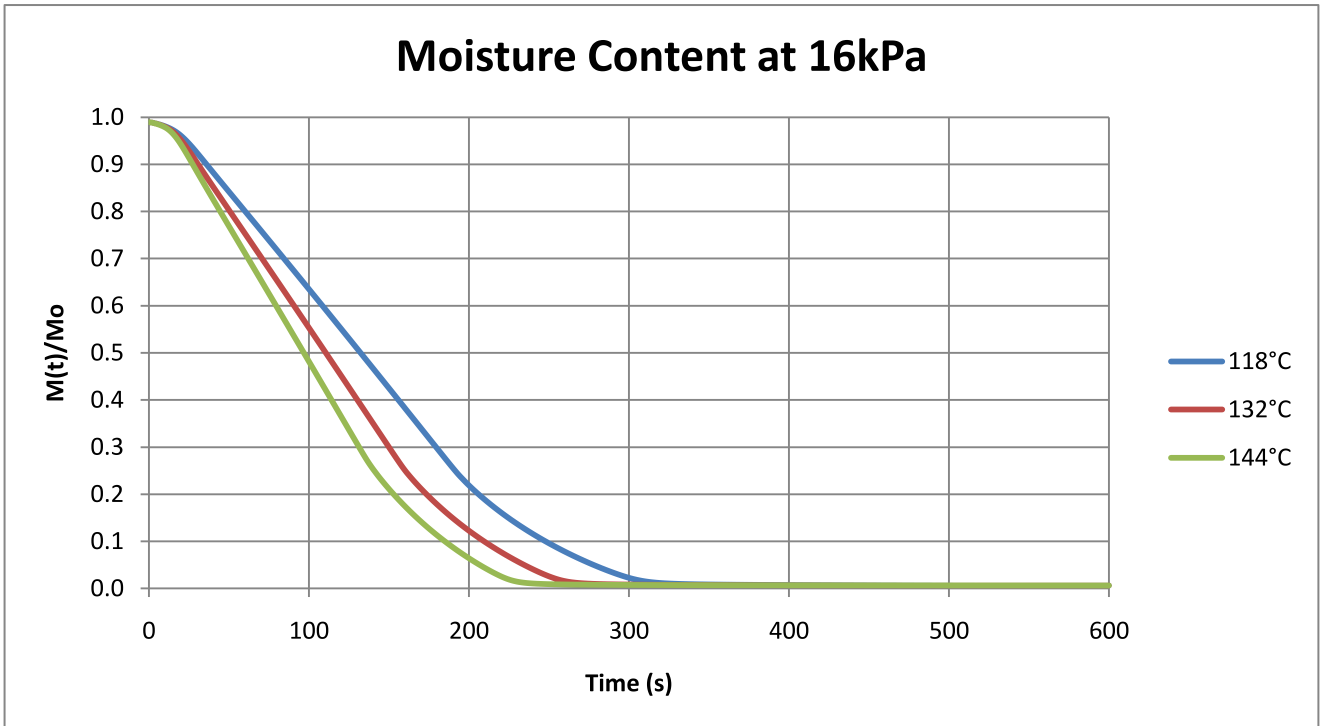


Figure 5: Average temperature throughout the potato over frying time. Compare with figure 4 to see how changes in temperature and changes in moisture occur together.

Figure 6: Moisture content over frying time at 16kPa when compared at different oil temperatures.



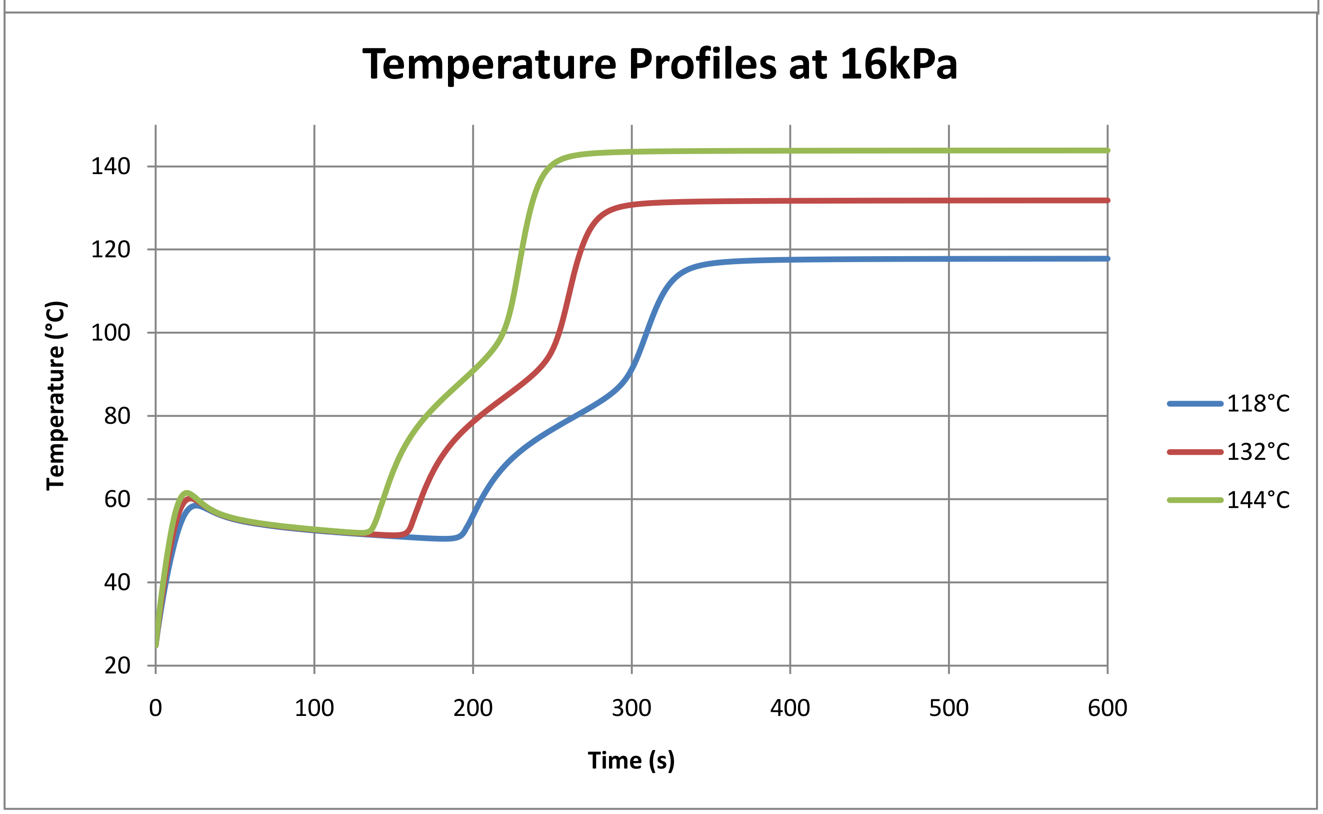
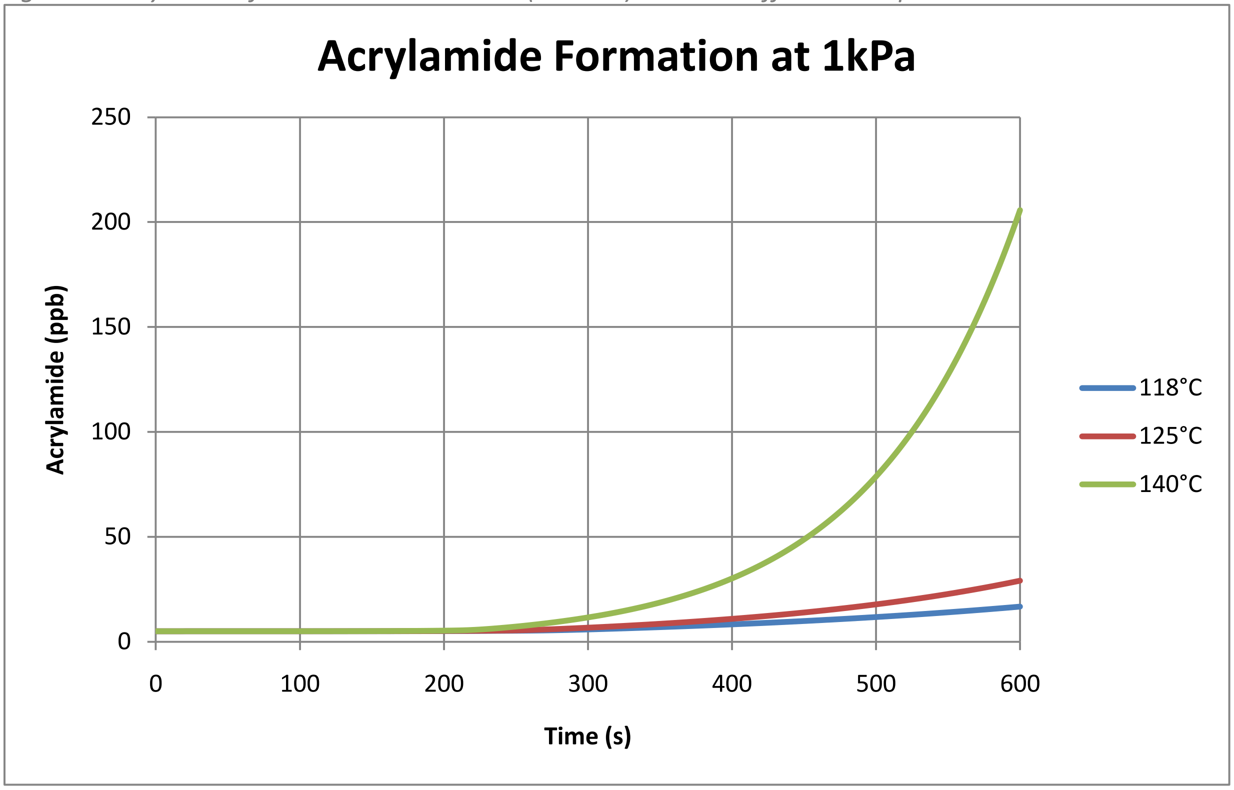


Figure 7: Temperature profiles over frying time when compared at different oil temperatures. Compare with figure 6

Figure 8: Acrylamide formation in a vacuum (1333Pa) at three different temperatures.



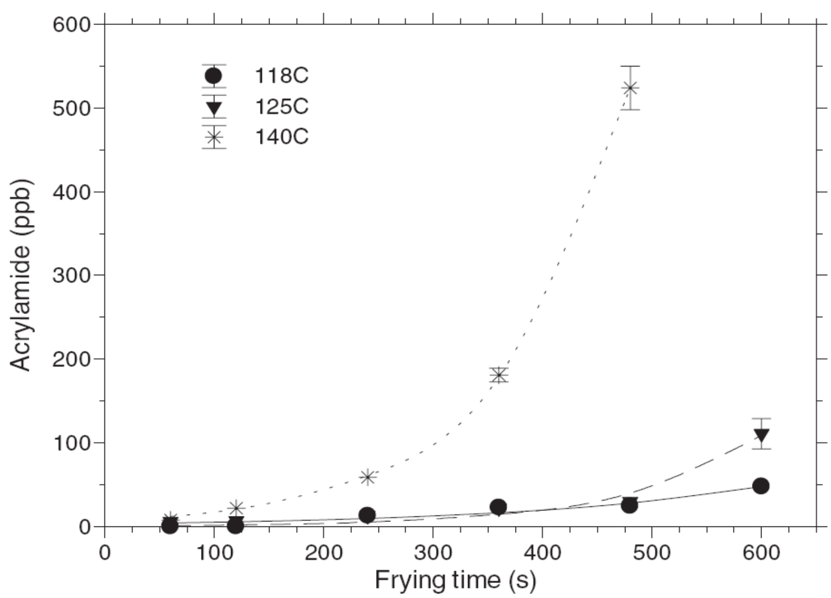
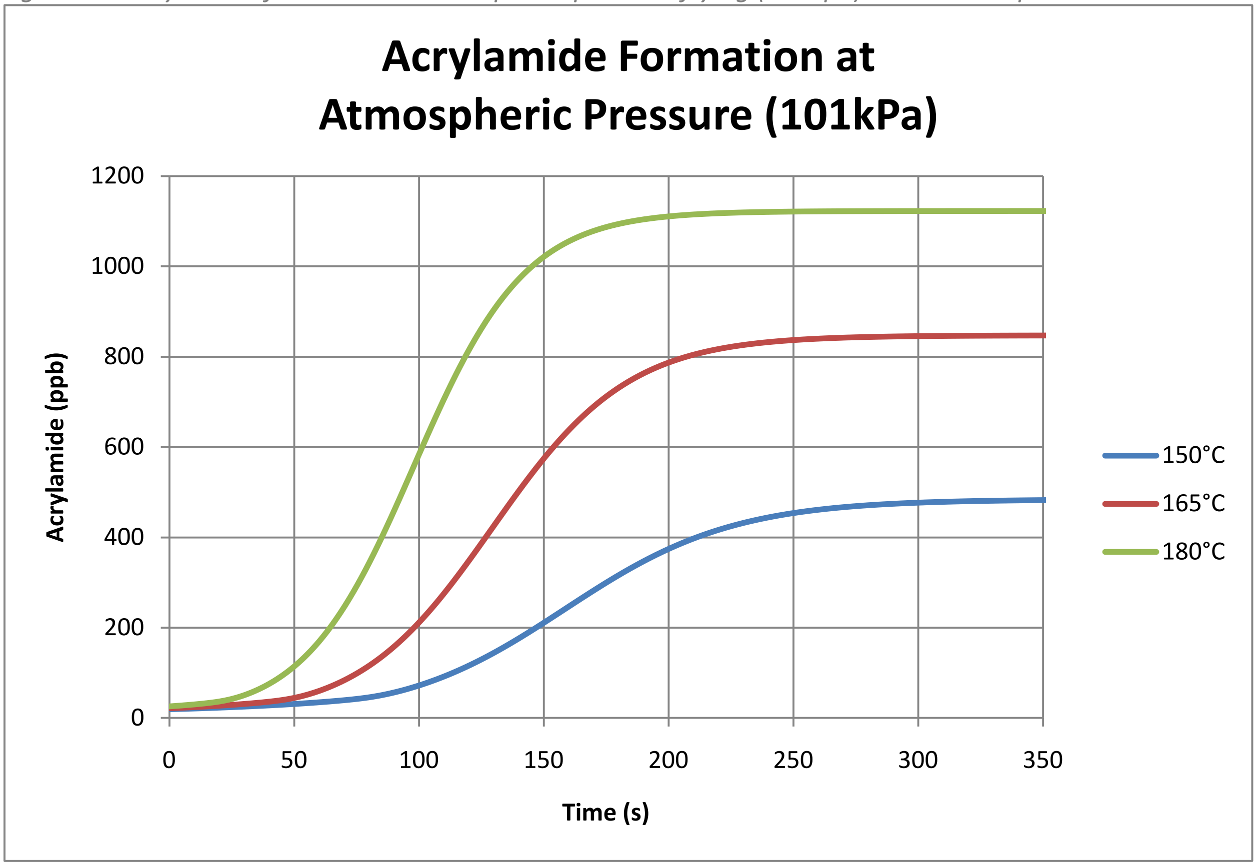


Figure 9: Granda and Moreira (2005) - Acrylamide formation in a vacuum (1333Pa) at various temperatures.

Figure 10: Acrylamide formation in atmospheric pressure frying (101kpa) at three temperatures.



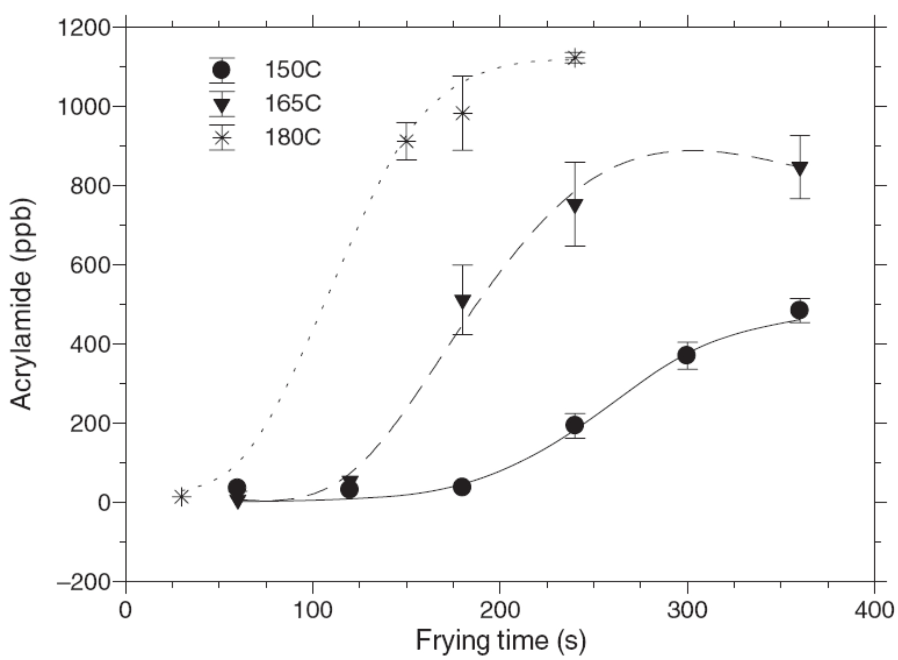


Figure 11: Granda and Moreira (2005) - Acrylamide formation in atmospheric frying (101kPa) at various temperatures.

Figure 12: Acrylamide content at four different pressures.

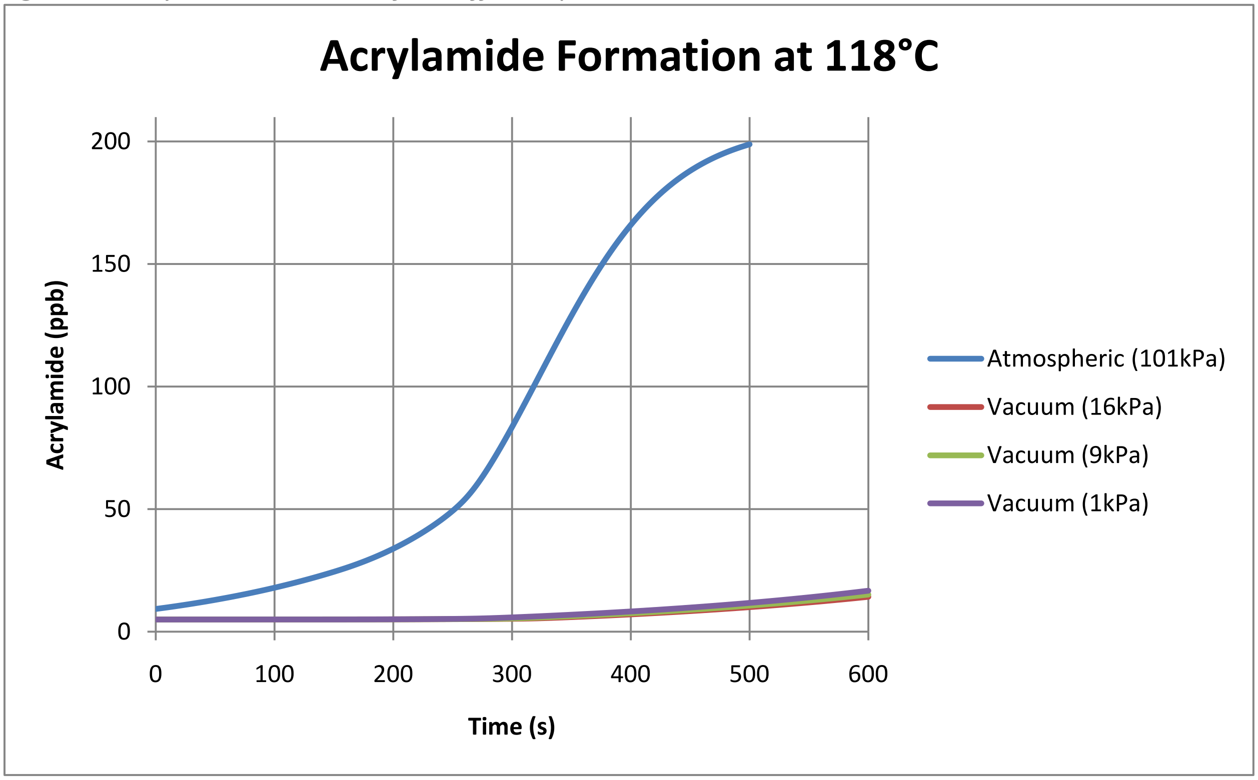


Figure 13: Acrylamide content at atmospheric frying (165°C) and vacuum frying (118°C). Differences between acrylamide formation here are significant.

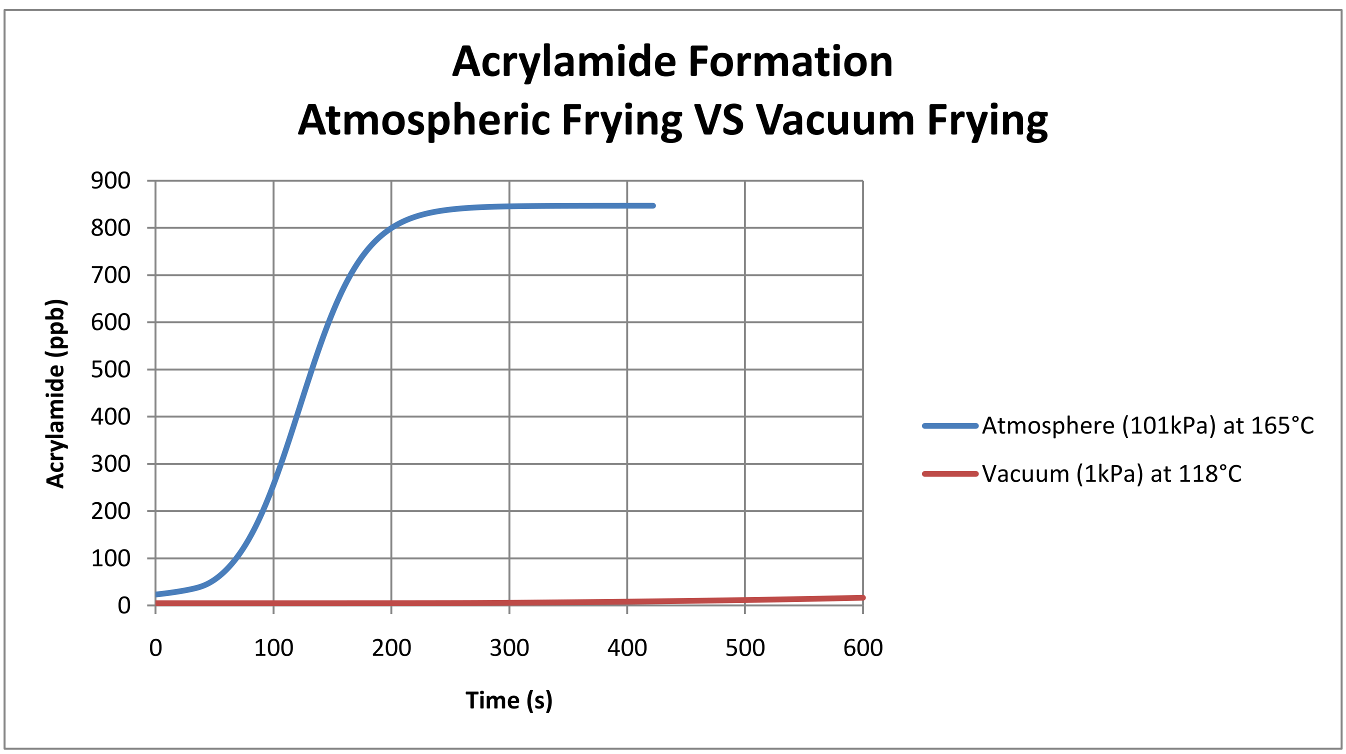
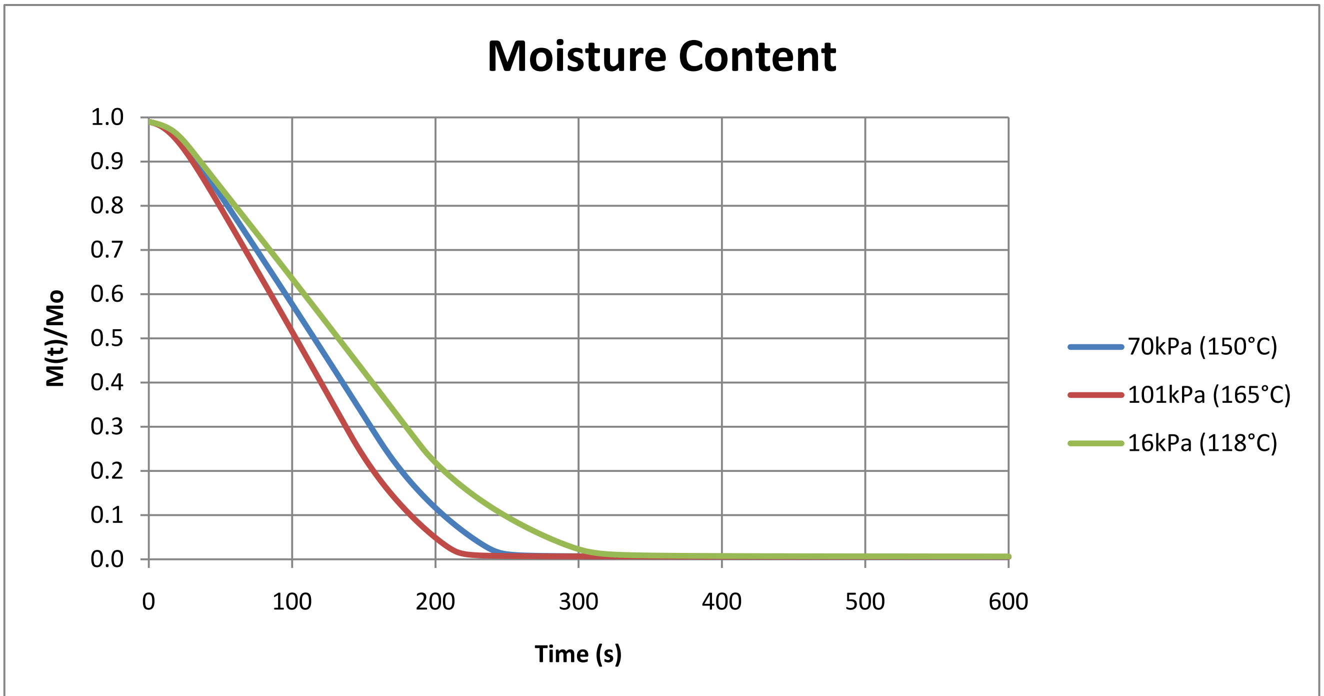


Figure 14: Moisture content to compare space frying (70kPa) to atmospheric frying (101kPa) and vacuum frying (16kPa)



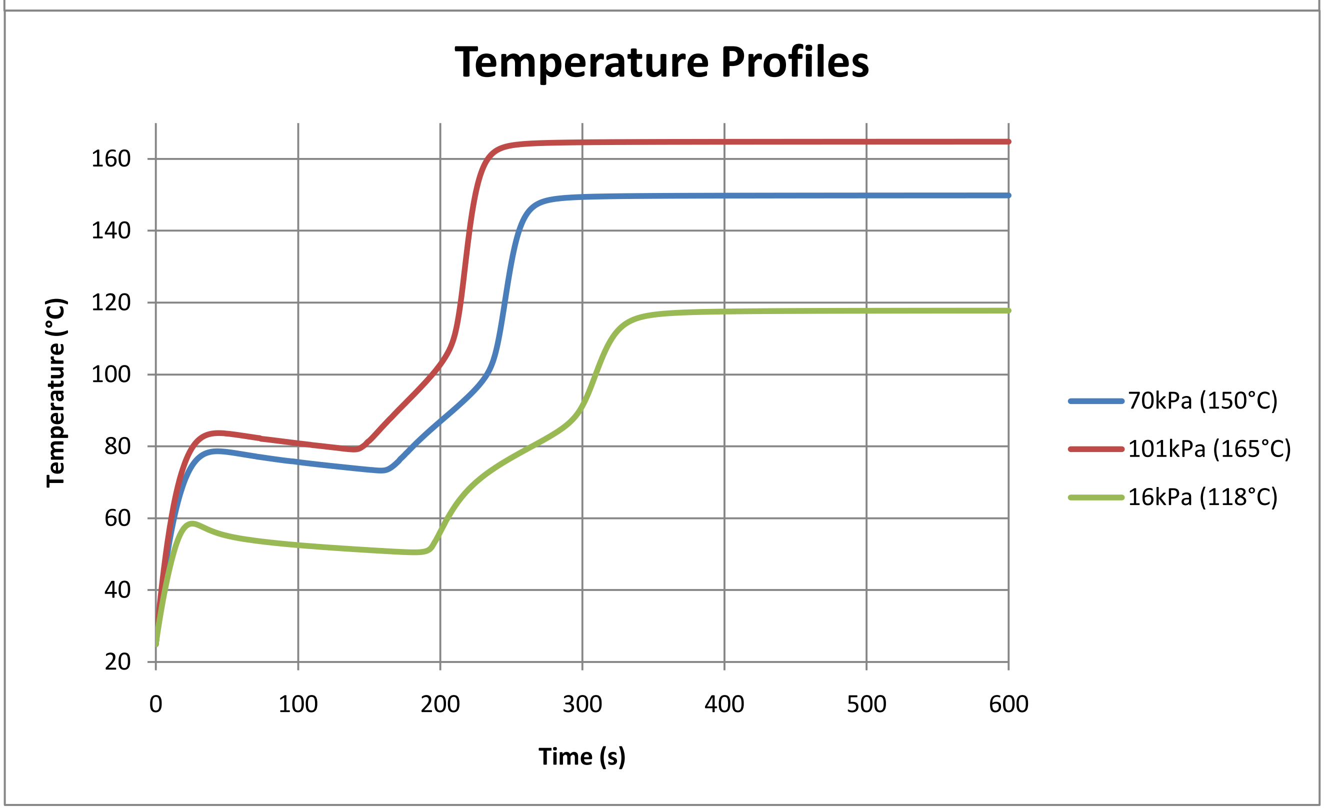
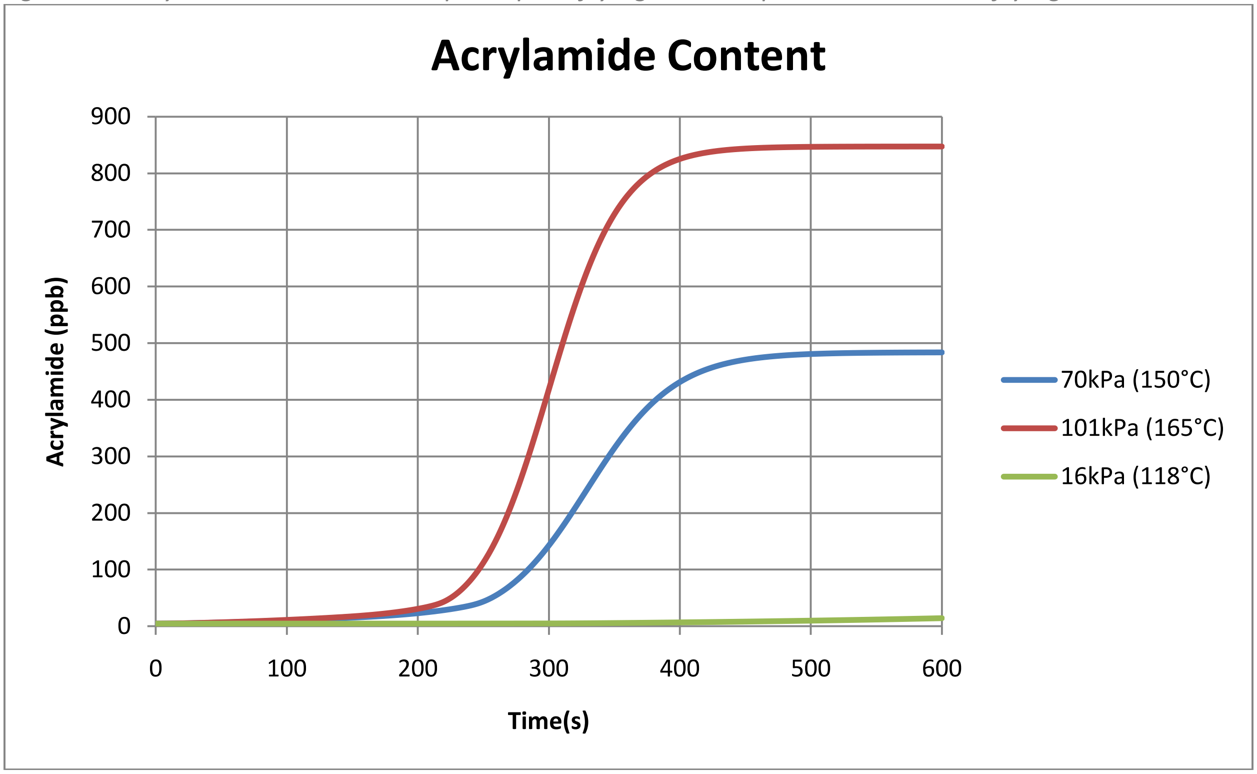


Figure 15: Temperature profiles of the same pressures and cooking temperatures as above.

Figure 16: Acrylamide content to compare space frying to atmospheric and vacuum frying.



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